

MODIS Semi-Annual Report, December 2002

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This report covers the **aerosol ocean** and **aerosol land** algorithm, and our involvement in the **NIR water vapor**, **cirrus** and the **fire** algorithms.

Main topics addressed in this period:

AEROSOL RADIATIVE FORCING

1. Using MODIS aerosol products to determine anthropogenic component of aerosol direct radiative forcing over oceans. (*Kaufman, Mattoo, Procopio*)

AEROSOL OVER LAND AND OCEAN

2. Validation and statistics of MODIS aerosol optical depth derived over land and ocean from 2000 to 2002 (*Remer, Levy, Kaufman, Ichoku, Chu*)
3. Validation of MODIS-derived aerosol optical depths during CLAMS experiment (*Levy, Martins, Remer, Kaufman*)
4. Consistency analysis of glint angle dependence of MODIS-derived aerosol optical depth over ocean (*Levy, Kaufman*)
5. V4 Validation of MODIS-derived aerosol optical depths in SAFARI 2000 (*Chu, Remer, Kaufman*)
6. Validation of MODIS-derived aerosol optical depths in ACE-Asia (*Chu, Kaufman, Remer*)

ALGORITHM ENHANCEMENT & DEVELOPMENT

7. Updates of smoke model in Southern Africa and revision of geographical boundaries for aerosol model selection (*Chu, Remer*)
8. Development of MODIS-Lidar inversion algorithm (*Kleidman, Kaufman*)
9. Cirrus cloud screening over land (*Li, Kaufman, Mattoo*)
10. River sediment screening in the coastal area (*Li, Kaufman, Mattoo*)

OTHER TOPICS

11. Absorption MODIS Lookup table and Combination Aeronet/MODIS retrievals (*Mattoo, Kaufman, Martins*)
12. Statistics/comparison of MODIS and GOCART aerosol properties (*Kaufman, Mattoo*)
13. Analysis of burn scars of US western states fires in 2000-2001 (*Li, Kaufman*)
14. Shipboard aerosol measurements in Caribbeans (*Ichoku, Remer, Kaufman*)
15. Enhancement/maintenance of the automated daily process of the generation of the MAPSS database from MODIS and AERONET aerosol and water vapor products (*Ichoku, Kaufman, Remer, Chu*)
16. MODIS aerosol global validation and data analysis (*Ichoku, Kaufman, Remer, Chu*)
17. MODIS fire data post processing (*Ichoku, Kaufman*)
18. Development of aerosol transport model (*Lapyonok, Dubovik, Kaufman*)
19. Papers published/accepted/submitted (*Kaufman, Remer, Chu, Ichoku, Martins, Levy, Kleidman*)
20. Conference and workshop (*Kaufman, Remer, Chu, Martins, Mattoo, Li, Kleidman, Levy, Ichoku*)

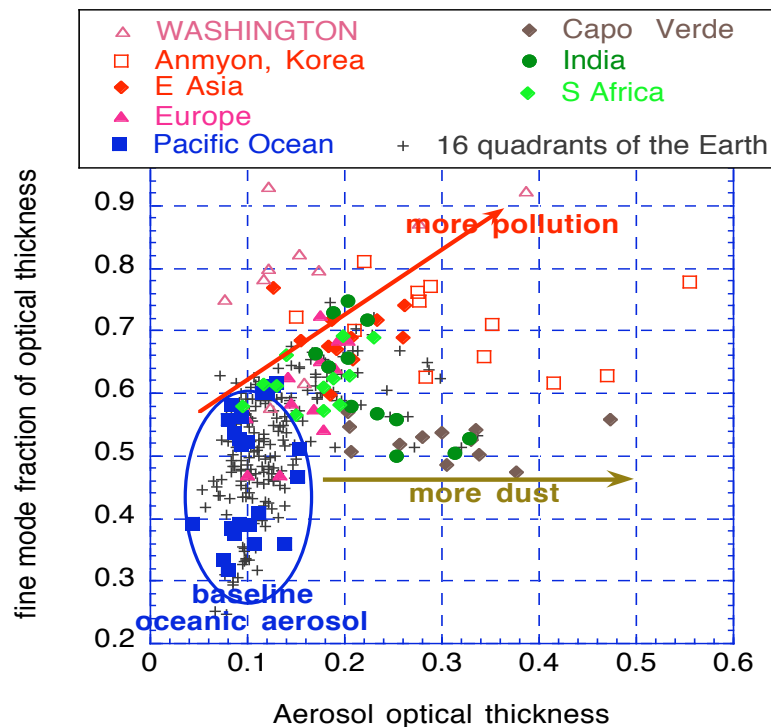
1. Using MODIS aerosol products to determine anthropogenic component of aerosol direct radiative forcing over oceans.

We use the MODIS derived spectral fluxes reflected at the top of the atmosphere to find the total reflected solar flux by aerosol. For this purpose we found weighting coefficients α_i that are used to represent the total solar flux, ΣF , as a function of the individual spectral fluxes in the MODIS channels:

$\Sigma F = \Sigma \alpha_i F_i$ where i is the MODIS channel, F_i is the reflected spectral flux normalized to the spectral solar irradiation and the coefficients, α_i , are:

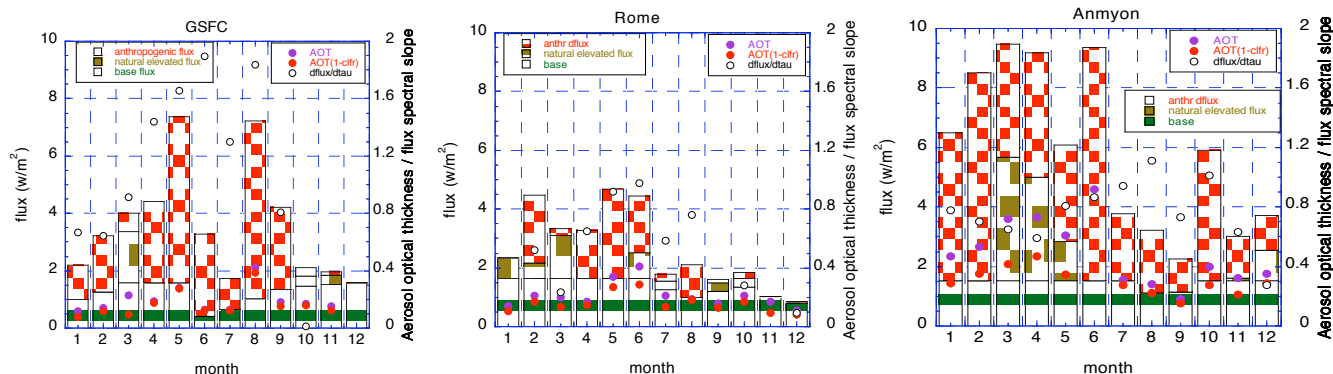
$$\alpha_{0.47}=1986\text{W/m}^2, \alpha_{0.55}=1871\text{W/m}^2, \alpha_{0.66}=1543\text{W/m}^2, \alpha_{0.86}=1003\text{W/m}^2, \alpha_{1.23}=460\text{W/m}^2, \\ \alpha_{1.65}=232\text{W/m}^2, \alpha_{2.13}=93\text{W/m}^2.$$

The fraction of the flux that is from anthropogenic sources is estimated using a two dimensional classification of the aerosols in different regions, using the MODIS measured optical thickness and the fraction of fine aerosol as the 2 dimensions:



Classification of the aerosol types measured by MODIS over the ocean by the aerosol optical thicknesses (AOT) in cloud free conditions and the fraction of the AOT in the fine mode. The classification is used to identify the base line aerosol, the anthropogenic component and dust. Note that variation of the baseline aerosol or the dust aerosol is for low fine fraction while the anthropogenic aerosol varies for high fine fraction. This difference is used to derive precisely the contribution of the anthropogenic aerosol to the aerosol reflection of sunlight to space. The AOT represents monthly averaged obtained by weighting the daily aerosol optical thickness from each $1^\circ \times 1^\circ$ longitude and latitude by the fraction of the cloud free area.

The following are a few examples of applications to get the local monthly forcing:



Location	Annual average aerosol optical thickness at 0.55 μm over the ocean	Annual average fraction of the optical thickness due to fine mode aerosol at 0.55 μm – ocean	Radiative forcing over the ocean – estimate of the anthropogenic part - W/m^2 .
Washington 38°-40°N, 75°-77°W	0.18	0.80	-2.30
Rome 40°-42°N, 11°-13°E	0.18	0.63	-0.86
Anmyon 35°-37°N, 125°-127°E	0.35	0.71	-3.25
Sao Paulo 22°-24°N, 45°-47°W	0.14	0.75	-2.35
Male 3°-5°N, 72°-74°E	0.19	0.65	-1.23
Capo Verde 15°-17°N, 21°-23°W	0.33	0.52	-0.04

Monthly aerosol reflected radiative fluxes at the top of the atmosphere in three major continental metropolitan areas: GSFC (Washington) in Eastern US; Rome in central Europe and Anmyon in Korea, East Asia. The plots show the monthly contribution of the baseline aerosol (lower stirped regions), naturally elevated aerosol or mainly dust (granulated brown regions) and due to pollution and smoke aerosol dominated by fine aerosol (pink regions). Purple dot – monthly average AOT, red dot – monthly average AOT weighted by cloud free area. The annual average optical thickness, the fraction of it due to the fine mode and the anthropogenic forcing are given in the table.

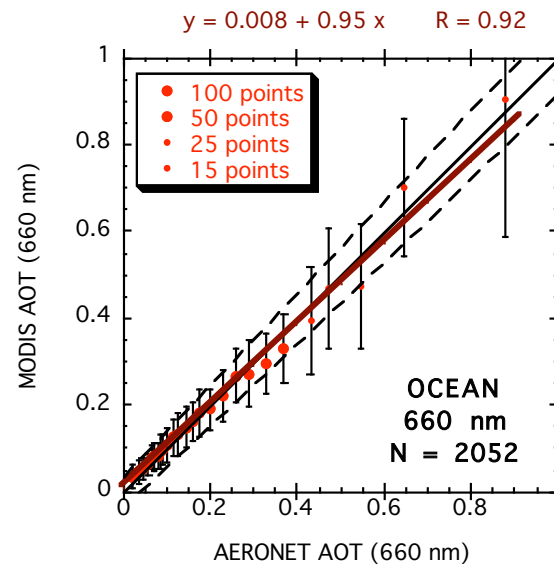
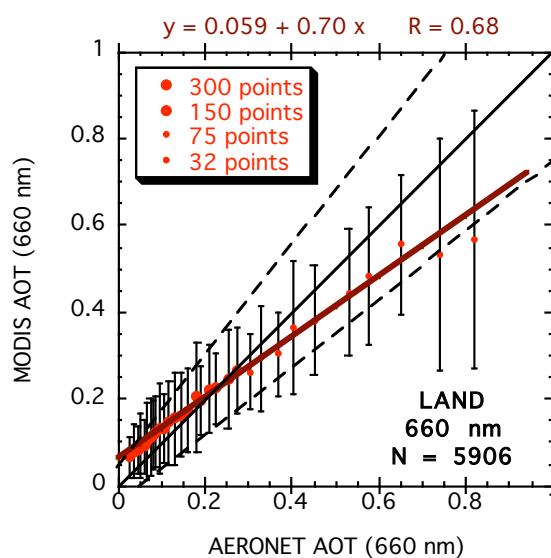
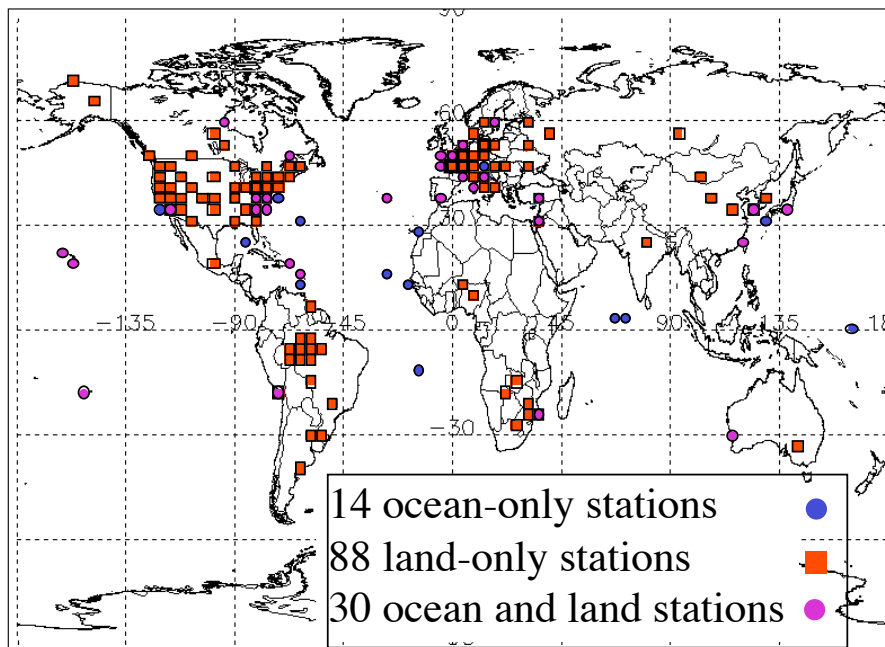
We plan to apply this method globally and extend it into the land

2. Validation and statistics of MODIS aerosol optical depth derived over land and ocean from 2000 to 2002

We completed the most extensive validation of the MODIS aerosol optical depth or of any satellite-derived aerosol product to date. Roughly 8000 MODIS retrievals (6000 over land and 2000 over ocean) were compared with co-located AERONET stations around the globe. (Figure below). Comparisons were made at 3 wavelengths for land algorithm (470 nm, 550 nm and 660 nm) and for the ocean algorithm (550 nm, 660 nm and 870 nm). Shown below are the scatter diagrams for the land and ocean comparisons at 660 nm. The data were sorted according to AERONET optical thickness then average for every 300 points (land) and or every 100 points (ocean). As the data became sparser at higher optical thickness fewer points were included in the averages, as indicated on the plots. The error bars represent the standard deviations of each group of 300 or 100 points. The given regression fit is calculated through the original cloud of points before they were sorted and averaged. The dashed lines represent our pre-launch estimated uncertainty: $\pm 0.05 \pm 0.15 \square$ over land and $\pm 0.03 \pm 0.05 \square$ over ocean, where \square is the aerosol optical thickness. We expect 2/3 (1 standard deviation) of our retrievals to fall within the dashed lines.

Globally we are meeting this expectation. Even though we are within expectations, a bias and offset are apparent in the over land algorithm. Some of the bias will be eliminated in the

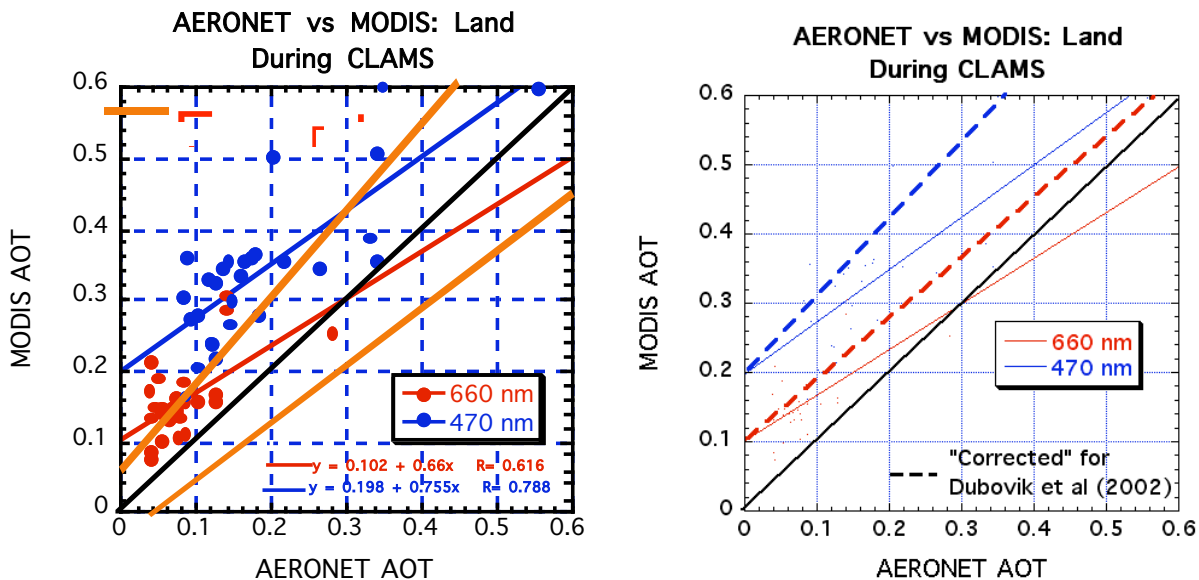
Version 4 algorithm with the addition of a more heavily absorbing aerosol model. Regional analysis reveals issues when expectations of aerosol model or surface conditions do not conform to our assumptions. However, the overall accuracy of the aerosol optical thickness product is excellent.

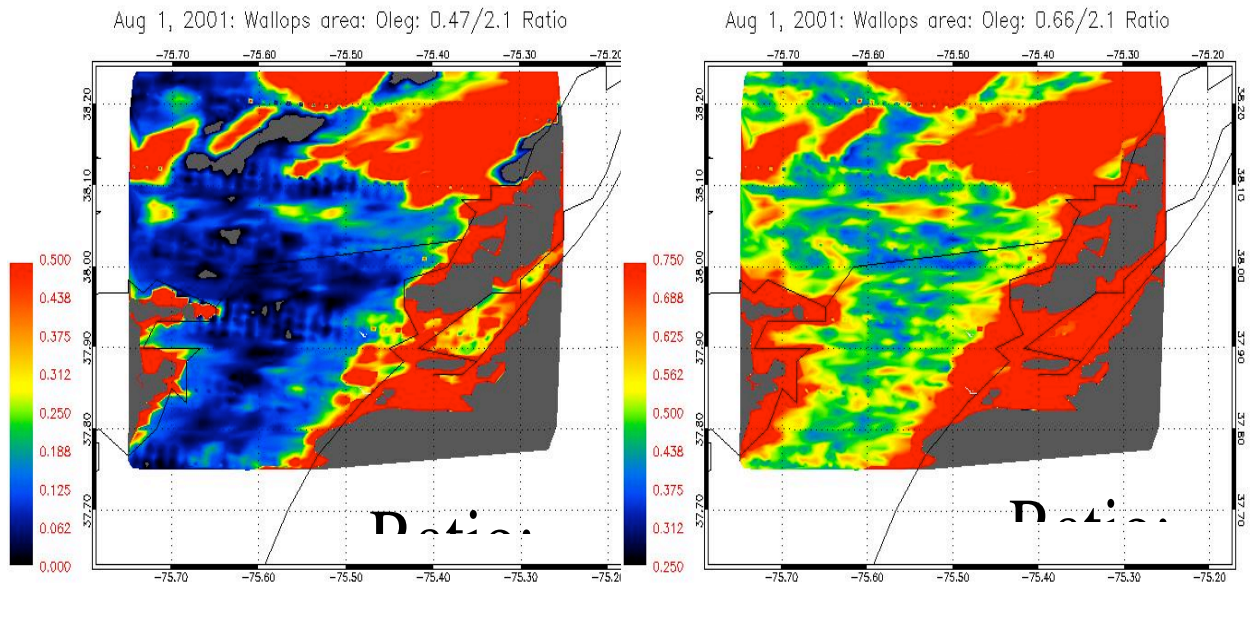


3. Validation of MODIS-derived aerosol optical depths during CLAMS experiment

The CLAMS validation of MODIS over land aerosol optical thickness versus AERONET compares averages of 50 km \times 50 km boxes of MODIS retrievals with one-hour time interval

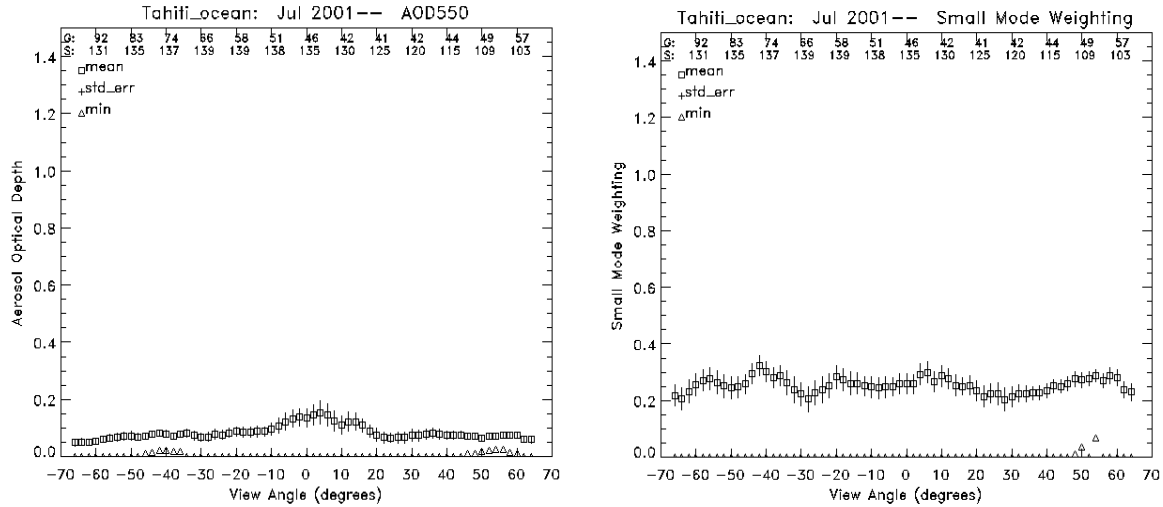
averages of AERONET sunphotometer measurements. The resulting regression equations are approximately $\tau_{\text{MODIS}} = 0.8 * \tau_{\text{AERONET}} + 0.1$, with correlation coefficient (R) ~ 0.7 . It is believed that the less than one slope and large offset are due to a combination of aerosol model and surface reflectance errors. The use of urban/industrial aerosol size distribution obtained from AERONET climatology at GSFC (Dubovik et al, 2002) produced better slopes (closer to one) than the operational urban/industrial aerosol models. The first set of figures below show aerosol optical depths derived by MODIS and AERONET during CLAMS at 0.47 and 0.66 μm wavelengths (upper left panel) and improvements using aerosol climatology model (upper right panel). Black line is one-one and orange lines are the expected “retrieval error ($\pm 0.05 \pm 0.2 \tau_i$)”. Significant improvement is seen in slope at 0.66 μm wavelength. The large bias (and offset) at 0.47 μm is likely related to errors in the assumed surface reflectance around Wallops, where water and sand contamination are likely. Using a MODIS image with an aerosol loading of less than 0.1, we performed an atmospheric correction. The second set of figures below show that the surface reflectance ratios around Wallops behave very differently than the assumed values of the operational algorithm. The left image shows that the reflectance ratio between 0.47 micron and 2.1 micron ($\rho_s^{0.47}/\rho_s^{2.13}$) varies substantially from the assumed value of 0.25. The right image is the reflectance ratio between 0.66 and 2.1 micron, which is closer to the assumed value of 0.5, but also varies substantially. In both figures, the coastal areas of the peninsula are bright red, exhibiting ratios > 0.75 , showing that water, sand and marshes introduce significant deviations from the algorithm assumed values and therefore introduce offset into the aerosol optical thickness product. Further investigation is still needed to resolve surface reflectance issue.





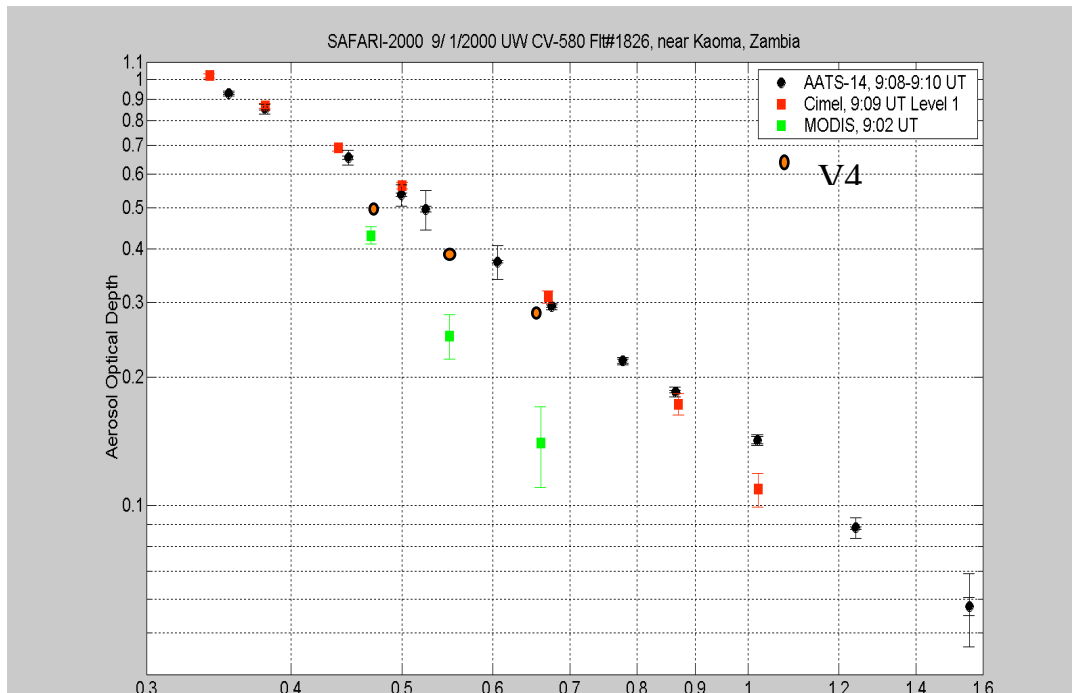
4. Consistency analysis of glint angle dependence of MODIS-derived aerosol optical depth over ocean

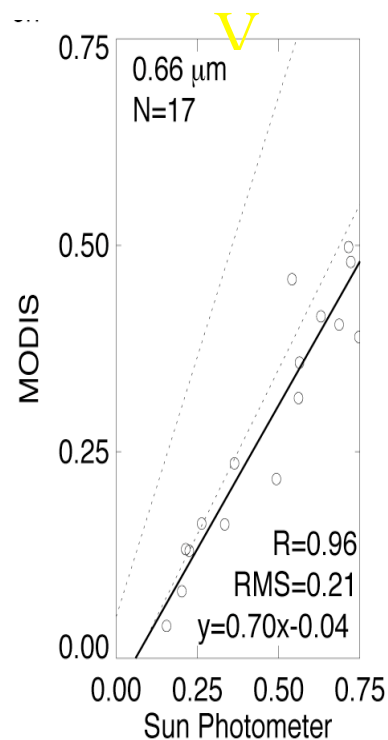
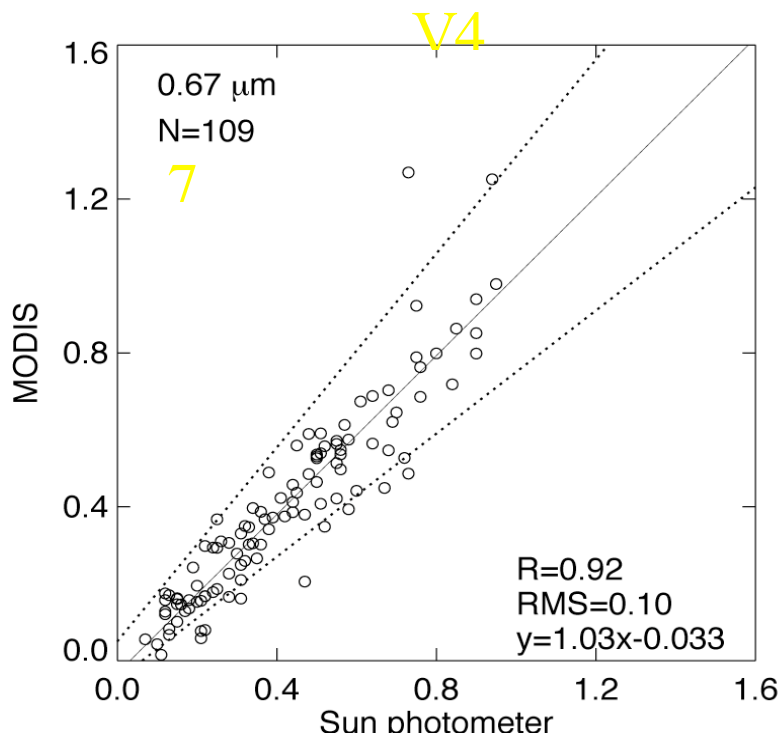
We are investigating MODIS aerosol retrieval consistency by examining retrieval dependence on scattering, view and glint angles over the ocean. Ten $5^\circ \times 5^\circ$ latitude/longitude boxes are selected around the globe, corresponding to known aerosol hotspots, plus a southern hemisphere latitude belt ($5^\circ \times 360^\circ$ lat/long). We computed monthly statistics from October 2000 to October 2001. With 5° latitude boxes, there is nearly a one to one correspondences between view angle and the other angles. Are there angular dependencies? Some of the analyses for some of the regions in some of the months indicate a correlation with angles. Further investigation will be needed to unravel whether these inconsistencies are due to a satellite problem, an aerosol phase function problem or a surface assumption problem. Shown below are MODIS-derived aerosol optical depths (at $0.55\mu\text{m}$) and fine mode fraction in Tahiti in July 2001. Some angular dependence is seen in these plots. Plotted are mean (squares) and standard errors (vertical lines). Standard errors are the standard deviation divided by the square of the number of retrieval days during the month (up to 31). Each point represents statistics on two degrees of satellite view angle, where negatives are the left side of a MODIS image. The numbers on the top represent glint angles (G) and scattering angles (S).



5. V4 Validation of MODIS-derived aerosol optical depths in SAFARI 2000

Low-biased MODIS aerosol optical depths are found in southern Africa during SAFARI 2000 field experiment when compared to AERONET sunphotometer measurements. In version 4, MODIS aerosol retrieval algorithm uses revised smoke model with single scattering albedo ~ 0.85 as opposed to 0.9 derived from biomass burning in South America. The biomass burning induced aerosol in Africa is more absorbing than that in South America because of high black carbon content. The figures show clearly the improvements due to the change in single scattering albedo. The upper panel is the comparison between MODIS and AATS (Ames Airborne Tracking Sunphotometer) at Koama, Zambia and lower panel is for MODIS and 7 AERONET sites in Zambia. At two AERONET permanent sites (Mongu and Skukuza), improvement is not as significant because biomass burning is not the only source of aerosols. At Skukuza, local pollution is the main contributor.



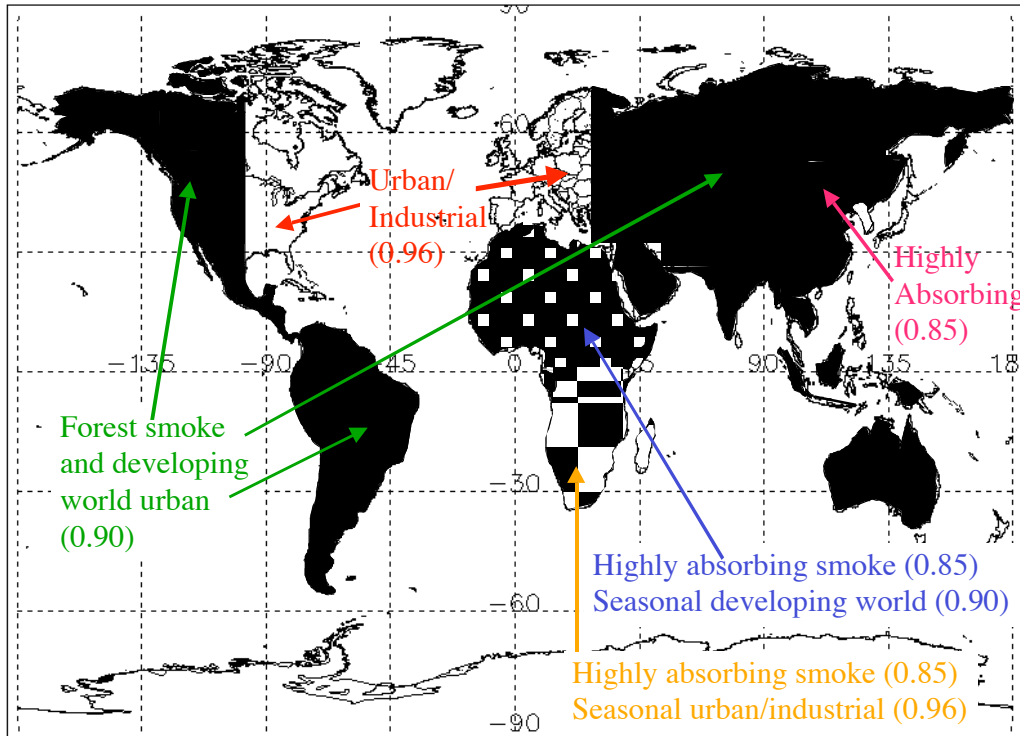


6. Validation of MODIS-derived aerosol optical depths in ACE-Asia

The MODIS-derived aerosol optical depths (τ_{λ}) are compared with AATS (Ames Airborne Tracking Sunphotometer) onboard C-130 and Twin Otter, and with radiometers and sunphotometers onboard NOAA R/V Ron Brown. MODIS-derived τ_{λ} values are generally higher when compared to AATS or radiometer/sunphotometer measurements in periods of dust events. The overestimated τ_{λ} values are related to scattering angle ($\sim 110^\circ$), which are thought to be the results of non-sphericity of dust particles. The phase function of spherical dust particle is significantly overestimated by as much as 50% compared to that of spheroid particle.

7. Updates of smoke model in Southern Africa and revision of geographical boundaries for aerosol model selection

As a result of the higher absorbing smoke aerosol in southern Africa, a moderately absorbing smoke model ($\tau_0 \sim 0.85$) has been added to the MODIS aerosol algorithm. The improvements are shown in item 4. Other changes are associated with the geographical boundaries for aerosol model selection. In eastern China, for example, aerosol model is changed from urban/industrial model to moderately absorbing smoke model. In Japan and Korean Peninsula, urban/industrial model is still assumed. The area of moderately absorbing smoke model extends further to east-Europe countries (formerly part of Soviet Union). These changes are based upon high black carbon content from airborne in-situ measurements (e.g., in ACE-Asia) and/or AERONET sky measurements. The revised map is shown below



8. Development of MODIS-Lidar inversion algorithm

The data obtained from MODIS and CPL (onboard ER-2) instruments during SAFARI 2000 field

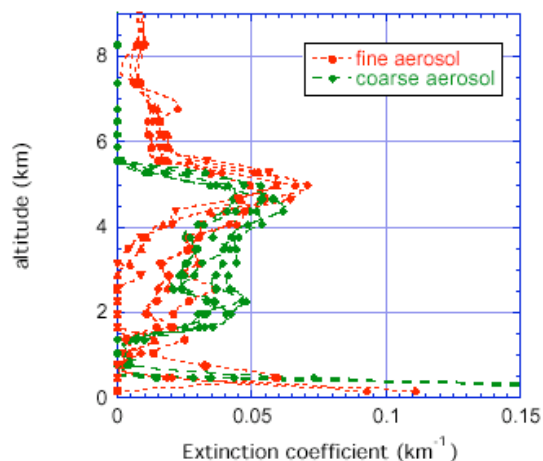
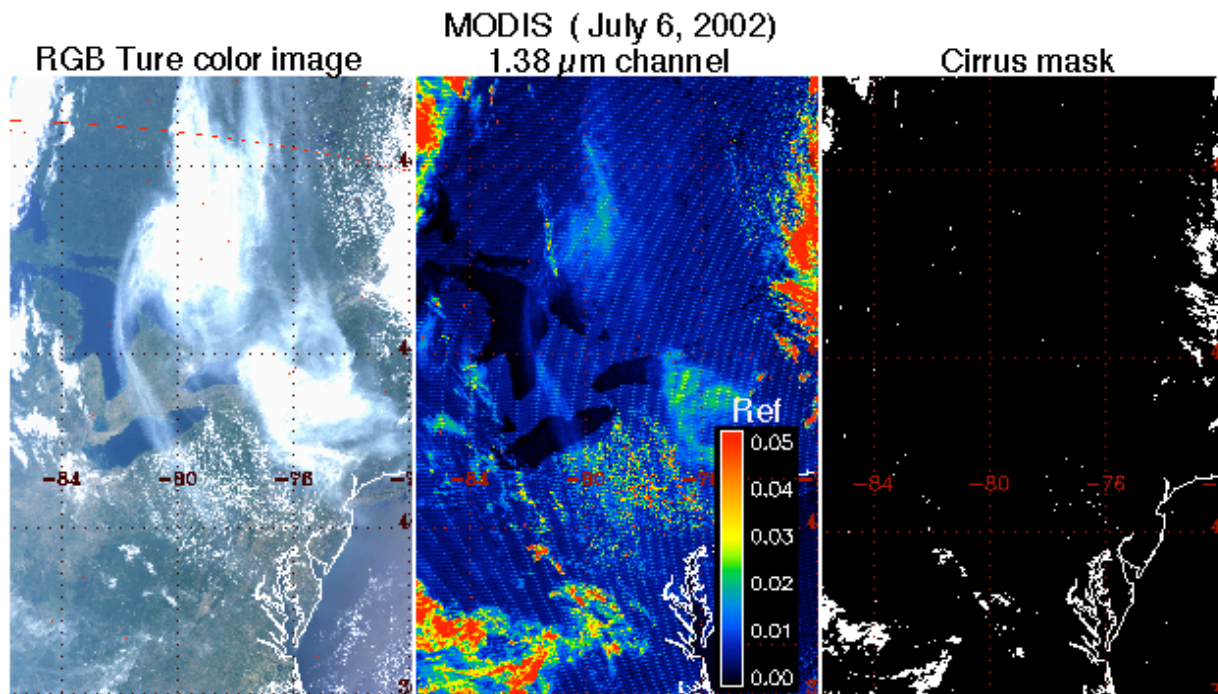


Fig. 5: Profiles of the extinction coefficients of the fine (red) and coarse (green) aerosol derived from the inversion of the lidar+MODIS data.

campaign are used to enhance the retrieval of aerosol information beyond the capabilities of each individual instrument. By combining both sensors, we can derive vertical profiles for both fine and coarse mode aerosols. Shown below are preliminary results using collocated MODIS and CPL measurements over ocean.

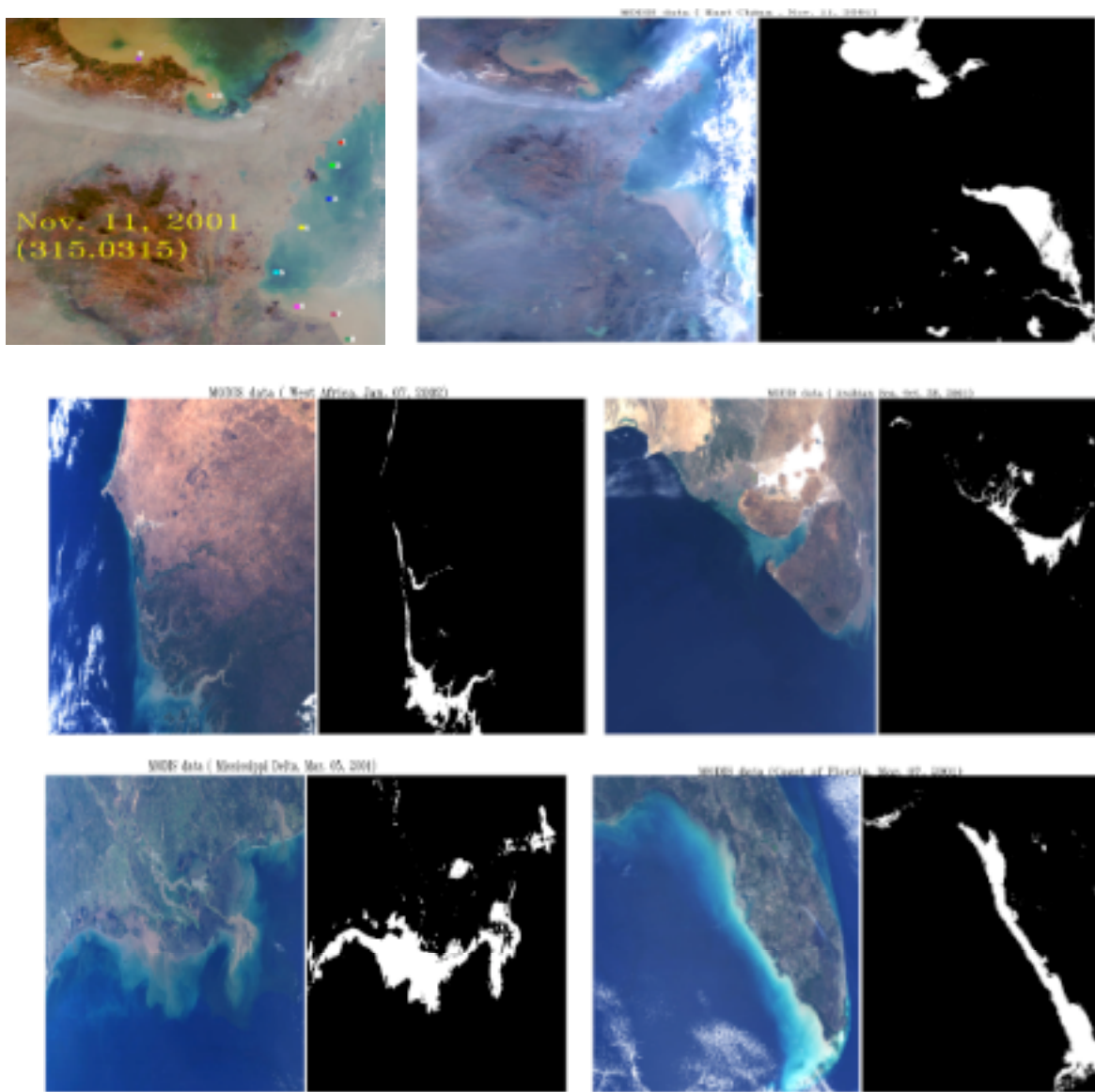
9. Cirrus cloud screening over land

Cirrus mask is tested over land on the case with transnational smoke on July 6 2001. The cirrus mask is based on the reflectance values of 1.38 μm channel and the ratio of the 1.38 μm to 1.24 μm channels ~ 0.3 . The heavy smoke is clearly not masked out by the criteria.



10. River sediment screening in the coastal area

River sediment has caused significantly high values in MODIS aerosol retrieval around river mouths because the existence of sediment reflects more sunlight back to space, which has been mistakenly treated as signal from aerosol backward scattering. Therefore, high aerosol optical depths are derived. Shallow water behaves similarly but with less intensity. The use of IR channels has shown good conditions to detect coastal turbid water and shallow water without masking out heavy aerosols. The sediment mask has been implemented into MODIS aerosol algorithm. Good results are shown with sediments being masked out, especially in East Asia. More tests are being done in Mediterranean near Israel. The sediment is shown in white.



11. Absorption MODIS Lookup table and Combination Aeronet/MODIS retrievals

The aerosol absorption measurements over sunglint require very accurate knowledge of the aerosol scattering properties. In preparation for AEROSAT ground work, this accuracy will be accomplished with angular polarization measurements still not available from space. In order to demonstrate this concept, a combination of AERONET and MODIS is used. The MODIS algorithm was modified in order to fit AERONET almucantar data and determine the aerosol models (particle size, and refractive index). Several LUT (Look Up Tables TABLE 1) were generated as a function of 4 single scattering albedos (1.0, 0.95, 0.85, 0.65), one wind speed (6 m/s), and 9 aerosol models (4 fine modes and 5 coarse modes).

Small particles:

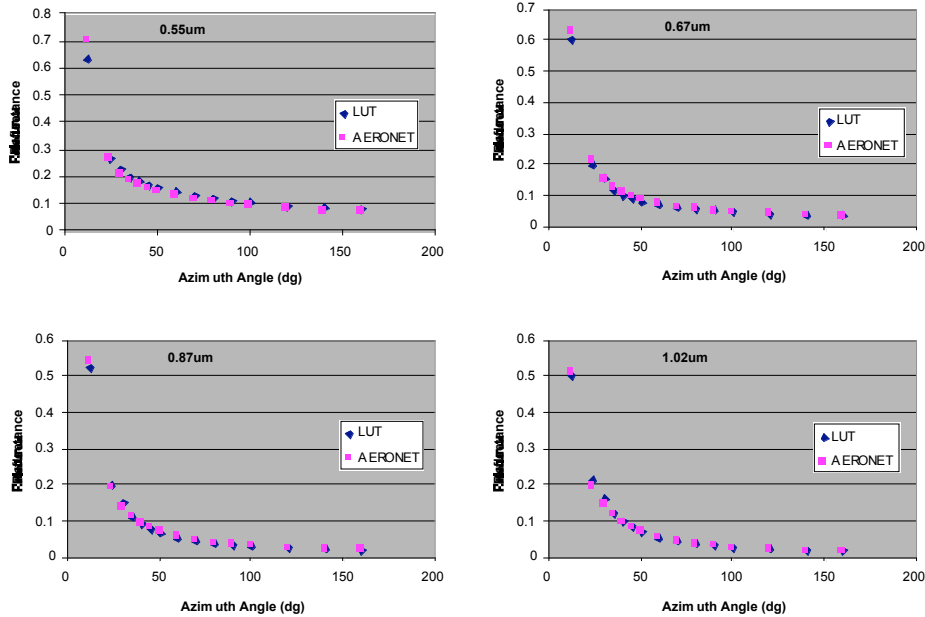
	$l=0.47\text{--}>0.86\text{mm}$	$l=1.24\text{mm}$	$l=1.64\text{mm}$	$l=2.13\text{mm}$	r_g	s	r_{eff}	comments
1	1.45-0.0035i	1.45-0.0035i	1.43-0.01i	1.40-0.005i	0.07	0.40	0.10	Wet Water Soluble type
2	1.45-0.0035i	1.45-0.0035i	1.43-0.01i	1.40-0.005i	0.06	0.60	0.15	Wet Water Soluble type
3	1.40-0.0020i	1.40-0.0020i	1.39-0.005i	1.36-0.003i	0.08	0.60	0.20	Water Soluble with humidity
4	1.40-0.0020i	1.40-0.0020i	1.39-0.005i	1.36-0.003i	0.10	0.60	0.25	Water Soluble with humidity

Large particles:

	$l=0.47\text{--}>0.86\text{mm}$	$l=1.24\text{mm}$	$l=1.64\text{mm}$	$l=2.13\text{mm}$	r_g	s	r_{eff}	comments
5	1.45-0.0035i	1.45-0.0035i	1.43-0.0035i	1.43-0.0035i	0.40	0.60	0.98	Wet Sea salt type
6	1.45-0.0035i	1.45-0.0035i	1.43-0.0035i	1.43-0.0035i	0.60	0.60	1.48	Wet Sea salt type
7	1.45-0.0035i	1.45-0.0035i	1.43-0.0035i	1.43-0.0035i	0.80	0.60	1.98	Wet Sea salt type
8	1.53-0.003i (0.47) 1.53-0.001i (0.55) 1.53-0.000i (0.66) 1.53-0.000i (0.86)	1.46-0.000i	1.46-0.001i	1.46-0.000i	0.60	0.60	1.48	Dust-like type
9	1.53-0.003i (0.47) 1.53-0.001i (0.55) 1.53-0.000i (0.66) 1.53-0.000i (0.86)	1.46-0.000i	1.46-0.001i	1.46-0.000i	0.50	0.80	2.50	Dust-like type

MODIS 2.1 μm data is used to determine the effective windspeed and this number is employed to correct the LUT at all MODIS wavelengths. As a result, the LUT can now be corrected for any desired “effective wind speed”. Finally, MODIS reflectances over the glint are interpolated to compute the aerosol single scattering albedo. The preliminary results of MODIS reflectance (derived from lookup tables) and AERONET almucantar measurements are shown below.

Fitting of Aeronet Almucantar with the Generated LUT



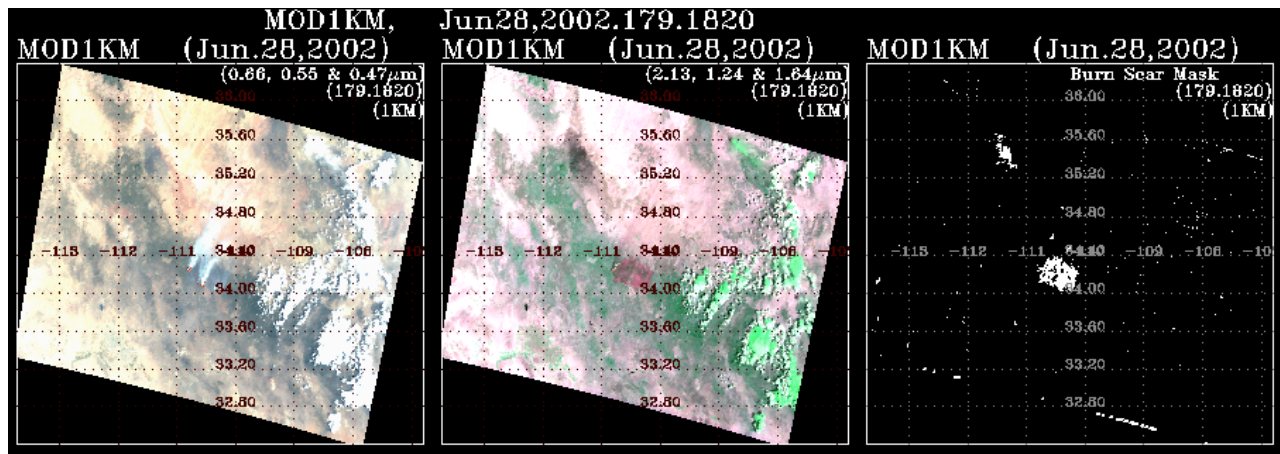
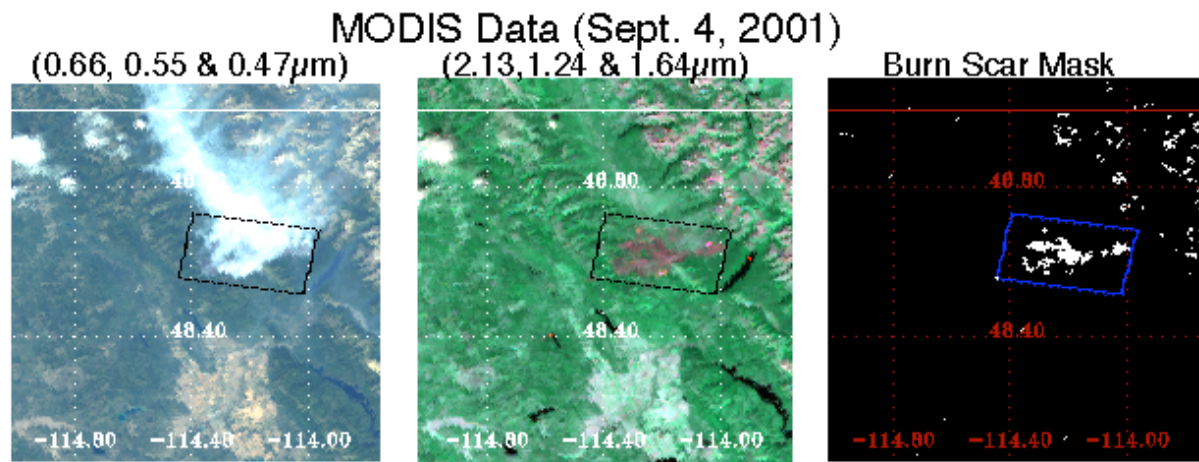
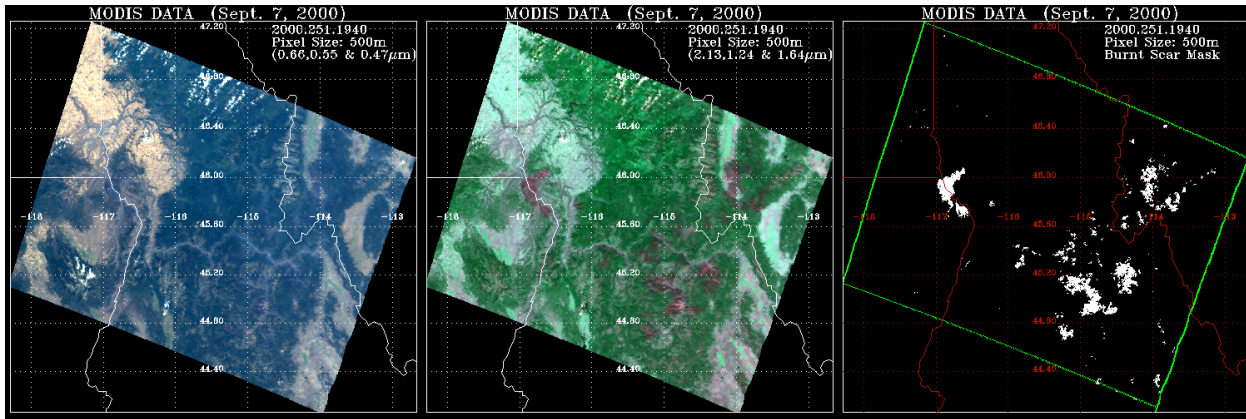
The good agreement between MODIS and the modeled results validate the ocean surface assumptions in the radiative transfer model used (Radtran) and the wind speed correction implemented in this work. The small differences observed (maximum about 6%) can be explained by calibration as well as by interpolation error in the LUT and the 9 discrete aerosol models.

12. Statistics/comparison of MODIS and GOCART aerosol properties

Software using L3 Daily MODIS data to generate L3 statistics was extensively modified to include components of fine and coarse mode optical depth like sulfates, organic carbon, dust etc from GOCART models. The data sets from GOCART model were prepared to be included into L3 aerosol products to generate a table for year 2001.

13. Analysis of burn scars of US western states fires in 2000-2001

The study of burn scars using MODIS spectral channels is to create burn scar mask for use in real-time monitoring by US Forest Service. Shown below are the events of US western states fires in 2000-2001. The verification of burn scars is underway using ASTER high resolution data.



14. Shipboard aerosol measurements in the Caribbean

During the period under review, we undertook a one-week over-ocean aerosol measurement mission aboard a ship cruising the eastern Caribbean Sea. Surface-based aerosol measurements are needed to validate MODIS aerosol retrievals globally. The Caribbean is one of the regions of the world where

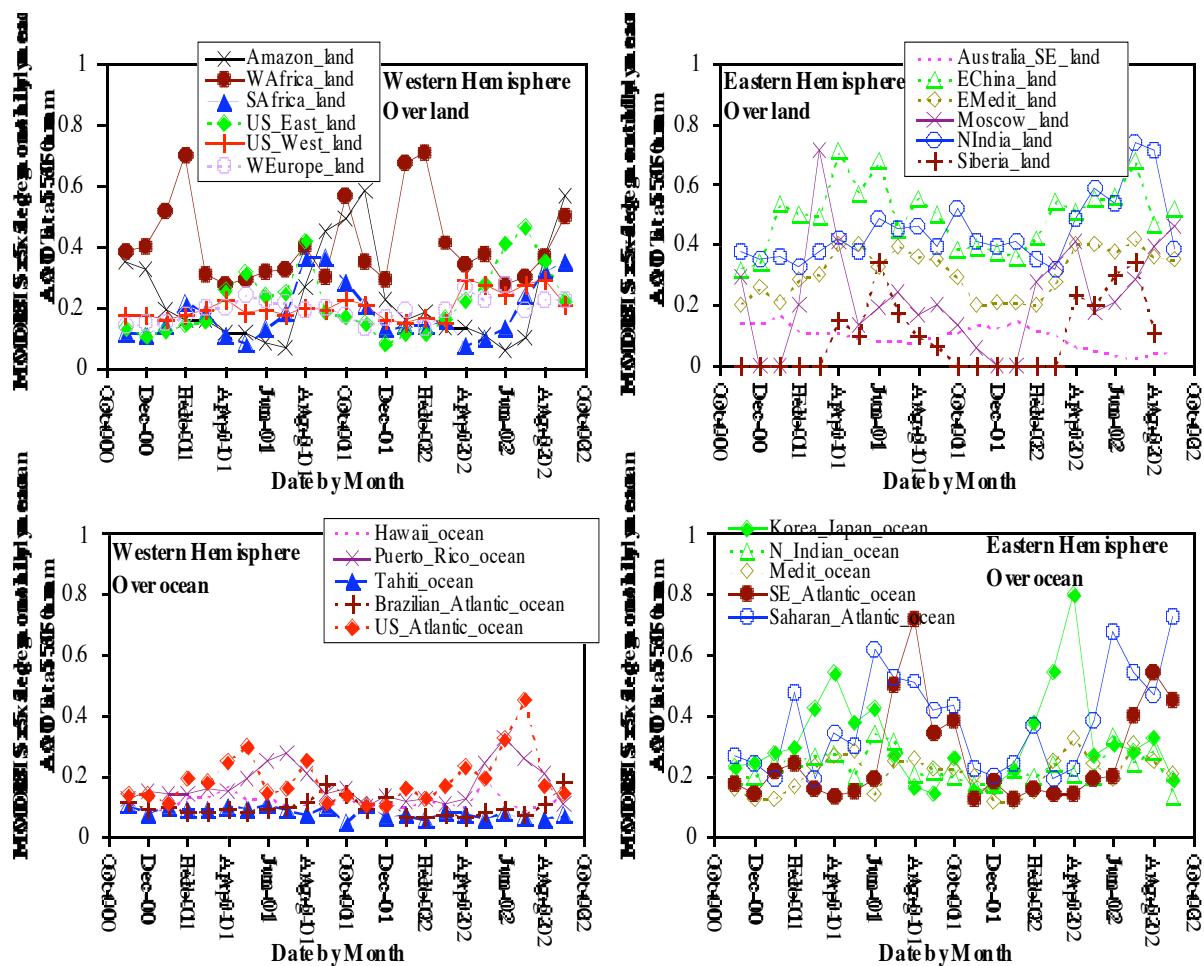
such data were hitherto not available, even though it is a very interesting region for aerosol studies in general and MODIS aerosol validation in particular, because of the impact of dust transported across the Atlantic from the Sahara. The mission lasted from July 27, 2002 to August 3, 2002. Three Microtops sun photometers with different wavelength combinations were employed for the aerosol optical thickness (AOT) measurements. Two of the instruments also had the capability to measure precipitable water vapor (W). Global Positioning Systems (GPS) receivers were attached to each of the sun photometers for regular location and time updates. The measurements were conducted in such a way as to cover both the Terra and Aqua overpass times, thereby providing data for evaluating the aerosol retrievals from the MODIS sensors onboard both satellites. Also, the mission provided an opportunity to have a close-up assessment of the aerosol dynamics of that region, including the intrusion of dust aerosol transported from the Sahara.

15. Enhancement/maintenance of the automated daily process of the generation of the MAPSS database from MODIS and AERONET aerosol and water vapor products

The MODIS Aerosol and associated Parameters Spatio-temporal Statistics (MAPSS) software/database system, which is the main data resource used for MODIS aerosol validation, needs continuous maintenance, especially necessitated by increasing data volume and changes due to product updates. During the period under review, the system was upgraded to handle data from Aqua-MODIS in addition to those of Terra-MODIS.

16. MODIS aerosol global validation and data analysis

Global aerosol concentration and size parameters derived from MODIS sensors onboard the Terra and Aqua satellites were evaluated with ground-based measurements and used for various aerosol studies. The MODIS aerosol parameters enabled a two-year assessment of aerosol loading and seasonal trends over several important regions on land and ocean, based on 5x5-degree monthly averages (see Figure). Similar studies were conducted at higher spatial (50x50-km) and temporal (daily) resolutions over selected sites representative of pollution, smoke, dust, and sea-salt aerosol types. Also, a two parameter clustering technique was employed successfully for categorizing the predominant aerosol types and events affecting selected locations over the Atlantic and Pacific Oceans.



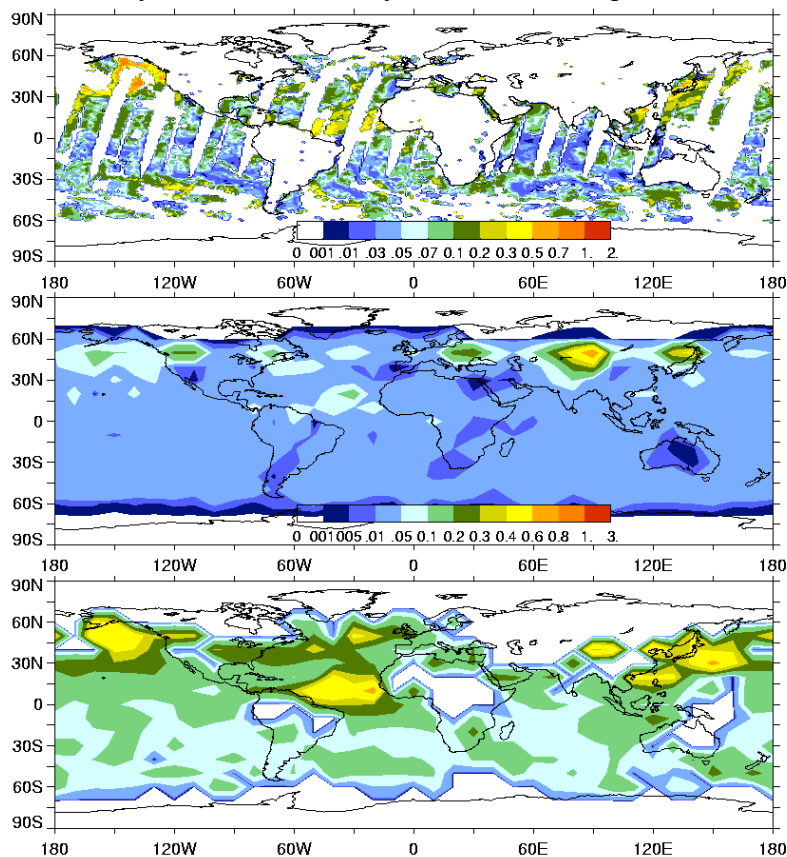
17. MODIS fire data post processing

During the period under review, routine extraction of MODIS fire data from its HDF format into the ASCII format was implemented. This was to create an easily accessible fire database, to facilitate MODIS fire data analysis. Also, tools were developed to calculate regional statistics of the fire data as well as those of corresponding aerosol data, to enable the planned joint analysis of both products.

18. Development of aerosol assimilation model

Efforts were focused on the global aerosol retrievals from MODIS and ground-based AERONET observations of desert dust emission sources. The developed inversion code with rigorous inversion technique and the GOCART transport model were used to retrieve the strength of aerosol emission sources that fit the aerosol fields observed by MODIS. The upper panel shows the MODIS and AERONET data on April 14, 2001; the middle panel shows retrieved emission sources retrieved (the sources assumed constant with one week); the lower panel shows the MODIS and AERONET data on April 14, 2001 as they reproduced by GOCART model with retrieved emission sources. The limitations of the applied technique: (i) coarse spatial resolution (10 x 10 degrees), (ii) emission sources assumed to be constant within a week.

The development of new version of the trace-back inversion algorithm has been started. In addition to already implemented rigorous inversion principles, this new version will use modified GOCART transport model. Using this adjoint technique will allow implementing the trace-back inversion without direct calculation of the huge dimension transport matrices and allows applying the spatial and temporal aerosol variability resolution used by GOCART transport model.



During this period the code calculating the kernel function accounting for polarization effects for spheroidal aerosol particles has been developed. The code uses T-matrix method for polydisperse randomly oriented particles by Mishchenko and the geometric-optics-integral-equation method by Yang and Liou. The look up table for retrievals of the aerosol optical parameters from AERONET measurements has been calculated.

19. Papers published/accepted/submitted

MODIS validation

1. **Remer, L. A., D. Tanré, Y. J. Kaufman, C. Ichoku, S. Mattoo, R. Levy, D. A. Chu, B. N. Holben, J. V. Martins, and R.-R. Li** and Z. Ahmad, Validation of MODIS Aerosol Retrieval Over Ocean, *Geophys. Res. Lett.*, 29(12), MOD 3, 1-4, 2002.
2. **Chu, D. A., Y. J. Kaufman, C. Ichoku, L. A. Remer, D. Tanre,** and B. N Holben: Validation of MODIS aerosol optical depth retrieval over land, *Geophys. Res. Lett.*, MOD 2, 1-4, 2002
3. **Martins, J. V., D. Tanré, L.A. Remer, Y. J. Kaufman, S. Mattoo, R. Levy,** MODIS Cloud

screening for remote sensing of aerosol over oceans using spatial variability, *Geophys. Res. Lett.*, MOD 4,1-4, 2002.

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20. Conference/workshop

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